Design of Gratings for Gain Equalization in WDM Optical Link

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Abstract: Wavelength division multiplexing (WDM) allows multiple channels to transmit the data at high speed at same instant. As signal travels longer distance they undergo attenuation, thus erbium doped fiber amplifiers (EDFAs) are used to amplify signals of all channels. But, it provides different gains to different WDM channels which in turn degrades the overall system performance. Thus, there is a need for equal amplifications of all channels. In order to achieve the flatten gain, cascaded fiber Bragg gratings (FBGs) are used. FBGs are designed depending on the desired reflectivity. In this paper, the performances of WDM optical communication system with and without gain equalizer are studied. The performance evaluations of the system are studied through calculating quality factor (Q), bit error rate (BER) and eye diagram. Thus, this technique can be used to achieve gain equalization of any arbitrary gain profile.

Keywords: Apodization, Erbium doped fiber amplifier (EDFA), Fiber Bragg gratings (FBG), Gain flattening, Wavelength division multiplexer (WDM).

Introduction

In optical fiber communications, WDM system combines many numbers of optical signals on to a single fiber by using different wavelengths of laser light. EDFA is a key device which can be used in WDM system in order to amplify the signals completely in optical domain. The advantages of EDFA are high gain, high output power, low noise and wide bandwidth [2]. However, different WDM channels will experience different level of amplification which in turn results in signal distortion and low signal to noise ratio (SNR). Hence there is need to enhance the WDM system performance and its transmission bandwidth by designing amplifier with flat gain or design gain equalizers that provide flat gain characteristics for all the channels in the WDM system. Intrinsic and extrinsic are the proposed methods to equalize the gain of EDFA. An intrinsic method uses the technique of modifying the spectroscopic properties of erbium ions by a change in co-doping or glass matrix. Fluoride based glasses [3] or Alumino-silicate [4] are such host matrices that enhances the flatness of EDFA gain profile. These methods equalize the gain over a shorter bandwidth. An extrinsic method uses a filtering device connected in series with the EDFA to equalize the gain [9]. Acousto-optic tunable filters [5], blazed gratings [6] or long period gratings [7] are the fiber filters that are previously demonstrated. Blazed gratings and long period gratings are susceptible to environmental conditions as they rely on coupling from non-guided to guided modes. The other gain equalization methods developed using chirped fiber Bragg grating [8] and variable optical attenuator (VOA) [10]. When large equalization bandwidth is required, the fabrication of chirped FBG becomes tedious. Chirped FBG provides same reflectivity for all the wavelengths. The limitation of VOA is its noise figure and high insertion loss.

Flat EDFA gain is obtained using cascaded short period apodized uniform FBGs, where there is no limitation on the number of WDM channels that to be equalized. The main advantages of FBG are low loss, high wavelength accuracy, high adjacent channel and cross talk suppression. Each channel in WDM can have different data rates and transmission formats. Thus system degradation can be efficiently reduced. The FBGs with different reflectivity are designed using OptigGrating 4.0 software from Optiwave Inc. The designed equalizer is incorporated in WDM system and simulated using OptiSystem 12.0 software from Optiwave Inc. and its performance is analyzed through calculating Q factor and bit error rate (BER). Section 2 briefly describes the FBG theory. Section 3 describes simulation setup of OptiGrating and OptiSystem. Section 4 presents results and discussions for EDFA gain flattening and describe the performance improvement of WDM System. Finally, section 5 gives the conclusion of the work.

FBG theory

A fiber Bragg grating is a type of distributed Bragg reflector constructed over a small segment of fiber that reflects particular wavelengths of light and all other remaining wavelengths are transmitted. This is achieved by creating a periodic variation in the refractive index of the fiber core. This is done by exposing the fiber core to ultraviolet (UV) light which causes variation in the refractive index of the fiber core. When the fiber core is exposed to two interfering UV beams, the gratings are imprinted in to the fiber. As a result, the radiation intensity varies periodically with the length of the fiber.The imprinted grating is represented as a uniform sinusoidal modulation of the refractive index along the core.

$$n(z) = ncore + \delta n[1 + \cos(2\pi z/\Lambda)] \tag{1}$$

where n_{core} is the core refractive index, δn is the photo induced change in the index and Λ is period of grating

$$\beta g - (-\beta g) = K = 2\pi/\Lambda \tag{2}$$

where βg is the propagation constant of the forward propagating guided mode, $-\beta g$ is that of the backward propagating guided mode.

The peak reflectivity R of the grating occurs when the Bragg condition holds at a reflection wavelength (λ_B)

$$\lambda_B = 2n_{eff}\Lambda \tag{3}$$

where n_{eff} is the effective refractive index of the grating in the fiber core.

At this wavelength, for the grating of length L the peak reflectivity R is given by,

$$R=\tanh^2 (kL) \tag{4}$$

Where the coupling coefficient k is given by,

$$k = \pi\Delta nI / \lambda_B \tag{5}$$

where I is a constant between 0 and 1.

Simulation Setup

OptiGrating

This technique requires FBGs to be connected in series with EDFA to flatten the gain. Different FBGs are designed using OptiGrating software. To equalize the gain of EDFA the reflectivities of cascaded FBGs are to be considered and they are adjusted based on the EDFA gain profile. Since, one FBG is responsible for equalizing only one channel, the number of FBG required is equal to the number of channels whose gains are to be modified to minimum one. The reflectivity of grating is related to the length of the grating, thus different reflectivity can be obtained by varying the grating length.

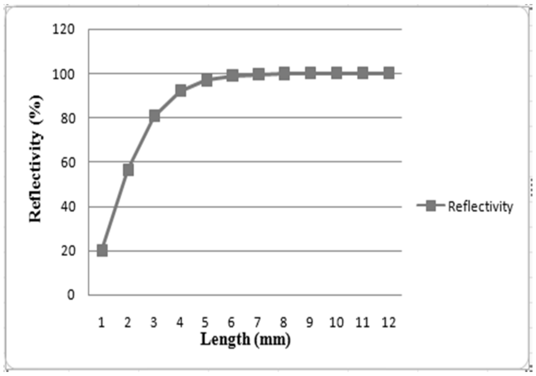

Figure 1(a).Reflectivity versus length

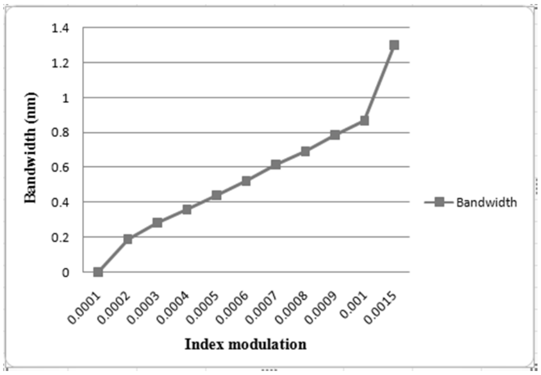

Figure 1(b). Bandwidth versus Index modulation

Fig 1(a) shows increase in reflectivity with increase in length and reaches 100% at some length. Thereafter, increasing length does not affect the reflectivity and Fig 1(b) show that bandwidth increases as the index modulation increases. By studying the behavior and the relation between several grating parameters, the optimal value for designing the grating is chosen.

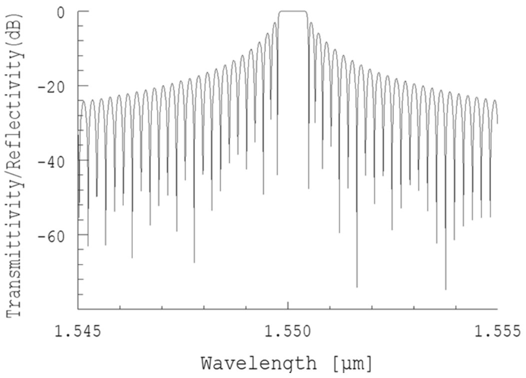

Figure 1(c). Reflectivity spectrum (no apodization)

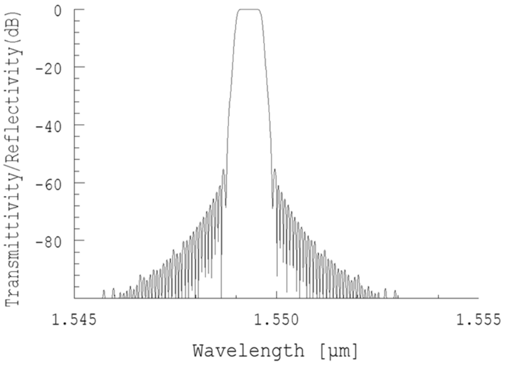

Figure 1(d).Reflectivity spectrum of grating with Blackman apodization

The reflectivity spectrum of uniform FBG is as shown in Fig 1(c). The performance of FBG is limited by the presence of side lobes. This problem is solved by introducing apodization into the grating design. In reflection spectrum the amplitude of the reflectivity will also be considered. In order to choose the best apodization profile, maximum suppression in the side lobe and reflectivity are considered. The effect of the apodization profiles on reflection spectra is analyzed using four different profiles: tanh, uniform, Blackman and raised cosine. The side lobes resulting from the different apodization profiles are listed in table1.

Table1. Side lobes of different apodization profiles

Apodization profiles	Side lobes(dB)
Without apodization	-3
Tan hyperbolic apodization	-20
Blackman apodization	-60
Raised cosine apodization	-80

Table1 shows that raised cosine apodization profile provides a better performance with optimal reflectivity and minimized side lobe. With raised cosine apodization, the side lobes are almost completely eliminated at the cost of reduced reflective power. The required reflectivity cannot be achieved suitably compared to Blackman. Thus Blackman apodization is used. The reflectivity spectrum after apodization is shown in Fig 1(d).

The function of Blackman apodization is,

$$(1+1.19\cos(y)+0.19\cos(2y))/2.38 \tag{6}$$

where $y = (2\pi(x\text{-Length}/2))/\text{Length}$

Table2. Grating design specification for a reflectivity of 90%

Parameters	Values
Operating wavelength	1550.12 nm
Core and Cladding refractive index	1.46& 1.45
Index modulation	0.0007
Effective refractive index	1.45
Average index	Uniform
Period Chirp	No chirp
Number of Segments	800
Grating length	3.9 mm
Grating period	0.5345241379 µm

OptiSystem

The simulation was carried out for the WDM system with and without gain equalizer using the OptiSystem 12.0 software from Optiwave Inc.

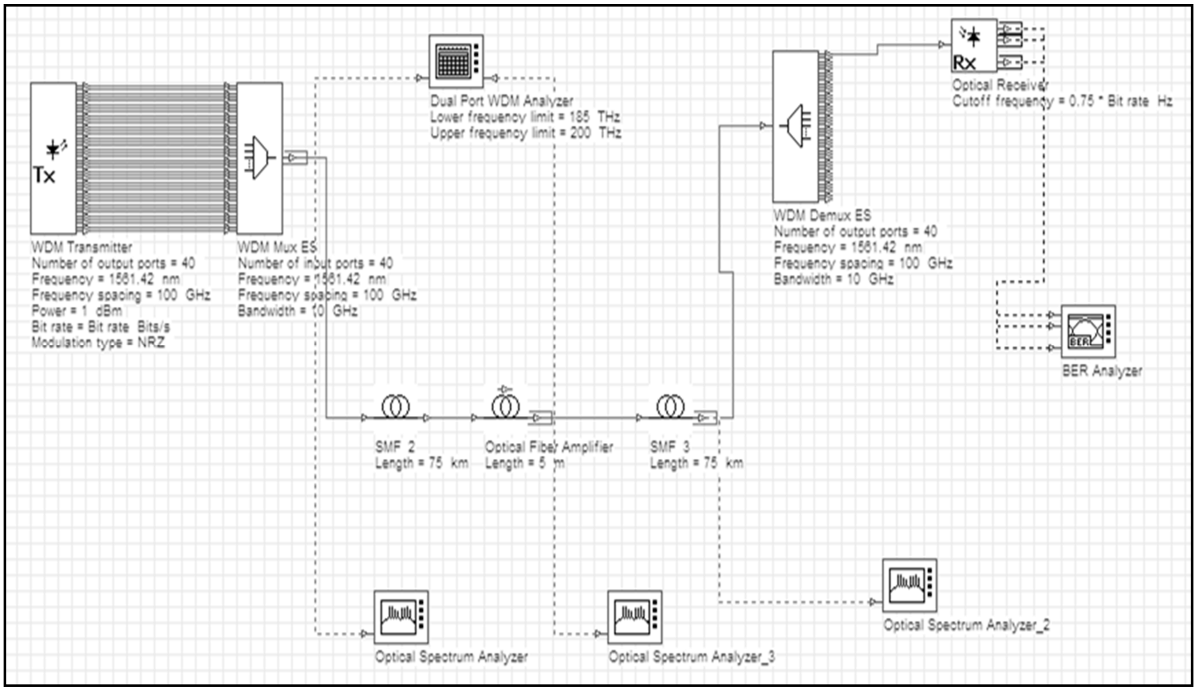

Figure 2(a). WDM system without gain equalizer

Fig 2(a) shows the complete system of 40 channel WDM system with EDFA. Forty channels which will cover the C-band 1530 to 1570 nm are generated at the transmitter. Frequency suppression of each channel is 100 GHz. The data rate used was 5Gbps and modulations used was NRZ type with input power 1dBm,. After modulation, the WDM channels were multiplexed and transmitted over a single mode fiber (SMF) of 150Km length, signal attenuation of 0.2dB/Km and without dispersion. The signal is passed to the EDFA that amplified the signal with unequal gains as shown in Fig 2(b).

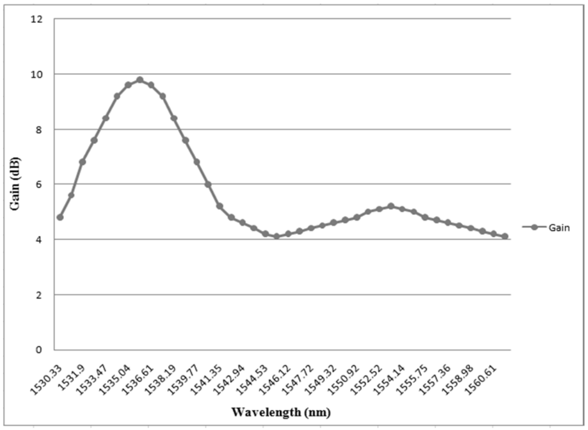

Figure 2(b). EDFA output gain versus wavelength

The EDFA of 5m long was used with forward pump wavelength 980nm and forward pump power 100mW. After passing through second SMF, 40 channels are separated by the WDM de-multiplexer and delivered to the receiver which consists of pin photodiode, low pass filter and BER analyzer. Pin photodiodes converts the optical signals to electrical signals. BER analyzer analysis the bit error rate, quality factor and eye diagram.

In order to equalize the EDFA gain output, we use cascaded apodized FBGs as shown in the Fig 2(c), of Bragg wavelengths identical to the wavelengths of the WDM channels. The condition for flattening the gain of the WDM channels is,

$$G_{EDFA}(\boldsymbol{\lambda}_n)[1-R(\boldsymbol{\lambda}_n)]= G_{EDFA,min} \qquad (7)$$

where $R(\boldsymbol{\lambda}_n)$ represents the peak reflectivity of FBG of Bragg wavelength $\boldsymbol{\lambda}_n$ such that n=1, 2,…., m-1. G_{EDFA} $(\boldsymbol{\lambda}_n)$ is the EDFA gain of a channel of $\boldsymbol{\lambda}_n$ wavelength and $G_{EDFA,min}$is the minimum EDFA gain of the channels.

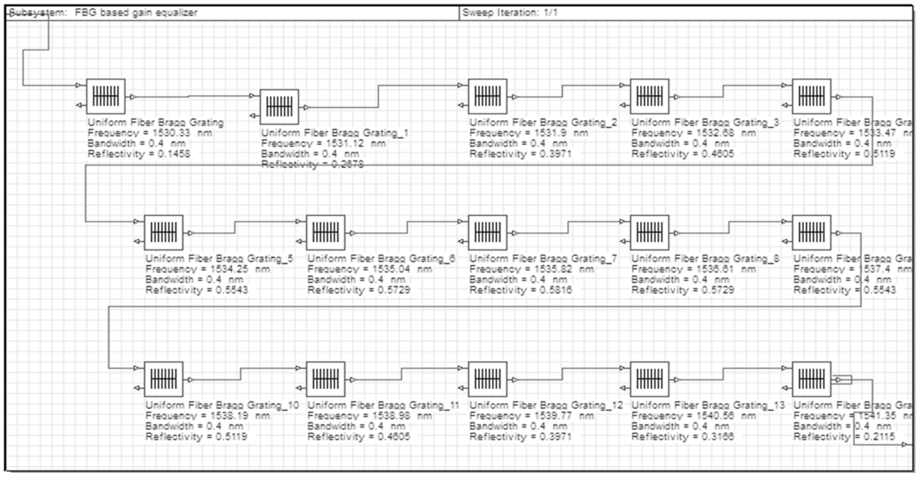

Figure 2(c). FBG based gain equalizer

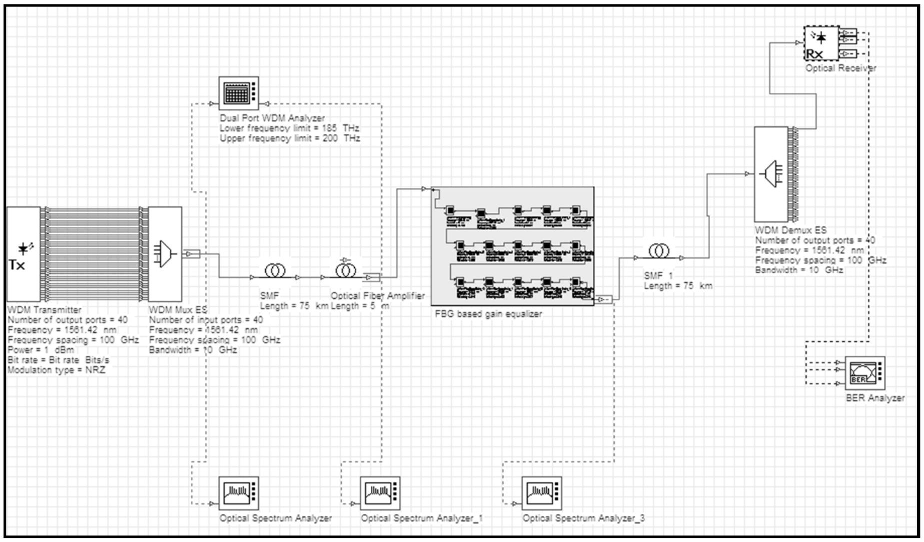

Figure 2(d). WDM system with cascaded apodized FBGs

The simulation was carried out by integrating FBG based gain equalizer to WDM system as shown in Fig 2(d). The EDFA output is passed through the gain equalizer which flattens the gain. Optical spectrum analyzer gives the power of different wavelength signals in dBm. The signal power spectrum at the output of WDM and power spectrum of amplified WDM channels before and after the cascaded FBGs are as shown in Fig 3.

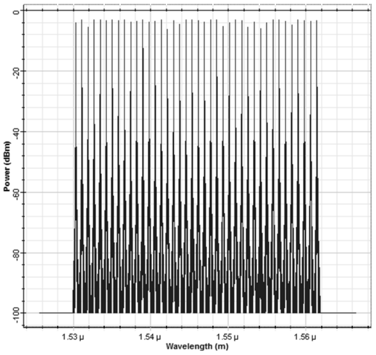

Figure 3(a). Power spectrum at the output of WDM

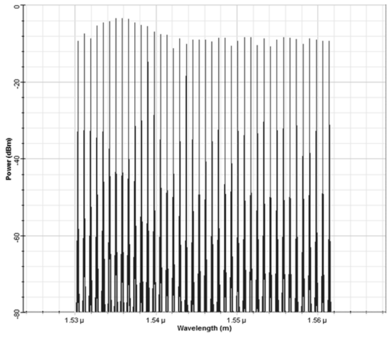

Figure 3(b). Power spectrum before cascaded FBGs

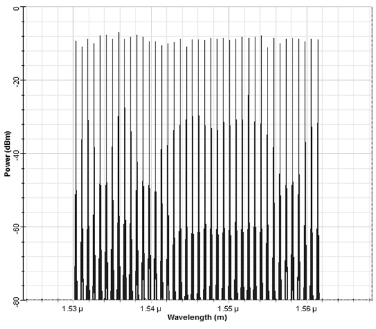

Figure 3(c). Power spectrum after cascaded FBGs

Results and Discussion

Analysis of system performance at different data rates

The quality factor decreases with the increase in the transmission distance. In practical, both 5 and 7.5gbps give a better Q factor of acceptable range. Comparatively, 5Gbps gives better Q factor for longer distance when compared to 7.5Gbps. Hence, simulation is carried out at 5Gbps. Fig 4(a) shows the quality factor comparison with respect to transmission distance at 5Gbps and 7.5Gbps.

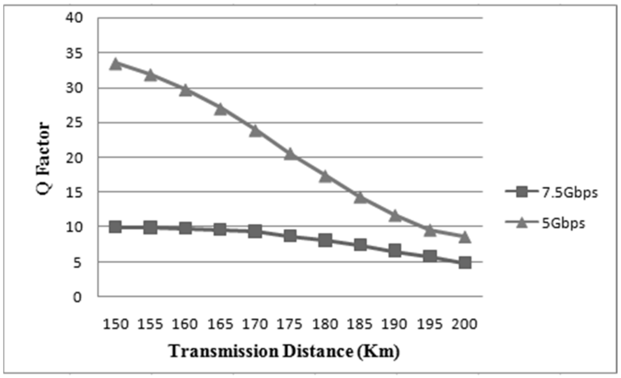

Figure 4(a). Performance of system at different data rates

Eye Diagram

Eye diagrams of WDM system with a gain flattening set are compared to those WDM system without gain flattening set at 150 km length, 5Gbps data rate are as shown in the Fig 4(b) and 4(c).With gain equalizer, the system provides better eye opening when compared to the actual system.

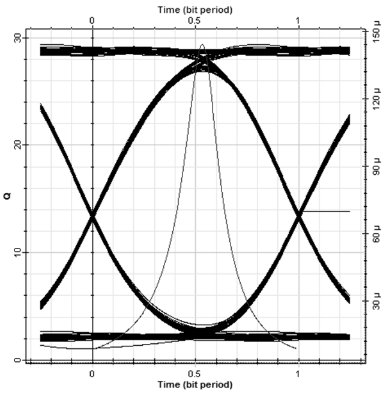

Figure 4(b).Without equalizer

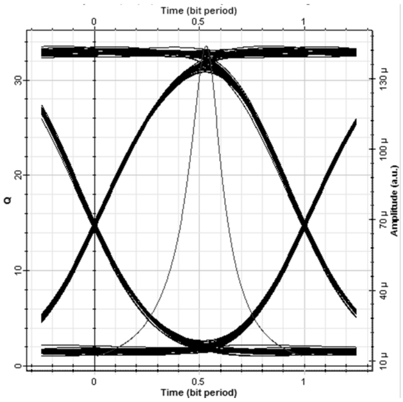

Figure 4(c). With equalizer

Quality factor analysis

It is analyzed that, the change in transmission distance impacts the quality factor which in turn affects the BER. The Fig 4(d) shows that the system with gain equalizer provided better Q factor and low BER compared to the system without equalizer. The table 3 represents Q factor, BER and eye height for system with and without cascading equalizer.

Table3. Parameters for analyzing the system performance

Parameter	Without cascading	With cascading
Q factor	29.363	33.567
BER	7.69183×10^{-190}	2.3914×10^{-247}
Eye height	0.000109502	0.000111049

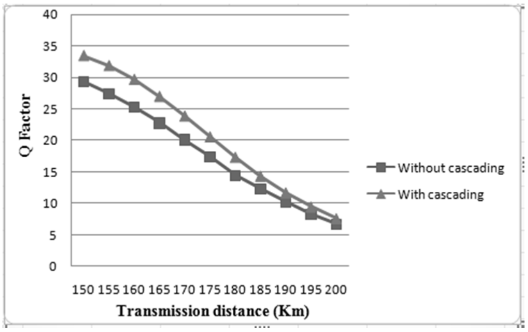

Figure 4(d). Change in fiber transmission distance effects on Q factor

Comparison of system performance with and without Dispersion

For longer transmission distances and higher bitrates, dispersion is a major concern. Hence, dispersion management system has been incorporated in to the optical link to study the behavior. The proposed technique provided good Q factor and eye opening when the dispersion is compensated. Fig 4(e, f) and Fig 4(g) shows the eye diagrams and Quality factor for the system with (16ps/nm.km) and without dispersion. Table 4 represents the Q factor, BER and eye height for system with and without dispersion.

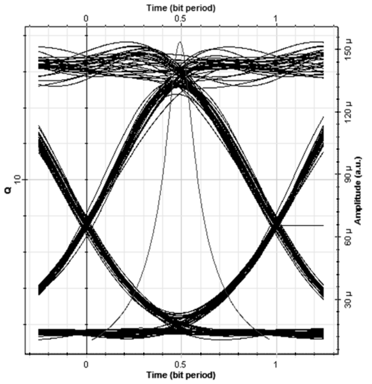

Figure 4(e).With dispersion

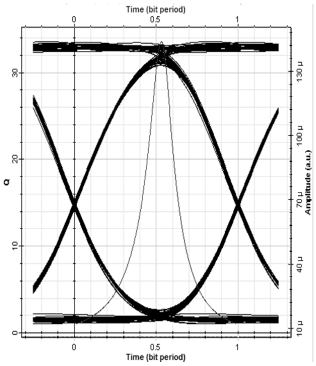

Figure 4(f). Without dispersion

Table 4. Analysis of system performance with and without dispersion compensation

Parameter	Without compensation	With compensation
Q factor	17.628	33.51
BER	$7.337\text{x}10^{-70}$	$1.524\text{x}10^{-246}$
Eye height	$9.911\text{x}10^{-5}$	$1.11\text{x}10^{-4}$

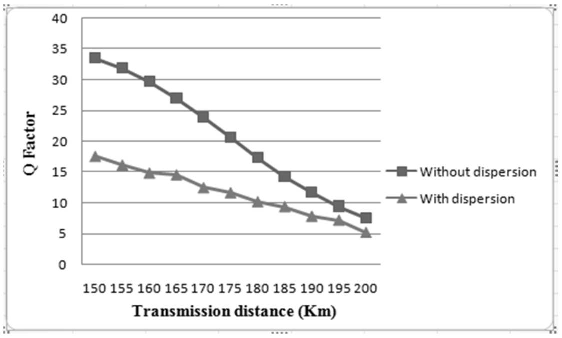

Figure 4(g). Performance of system with and without compensation

Conclusion

In this work, using cascaded apodized FBGs a flat EDFA gain was obtained. The reported technique is characterized by the ability to equalize any number of channels, ability to equalize any arbitrary profile and any level of reflectivity can be tuned, also FBGs does not introduces any noise and loss. Simulation results indicate that the WDM link performance is enhanced after gain equalization using cascaded FBGs. Q value is increased from 29 to 34. In addition to that, simulations are carried out for the WDM system with and without dispersion compensation. The system with dispersion compensation gave high quality factor from 18 to 34, small BER and good eye opening.

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